Fatigue Properties Of Squeeze, Semisolid And Gravity Diecast Al-Si-Mg Alloy

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ABSTRACT: Fatigue endurance properties are reported for squeeze, semisolid and gravity diecastings as measured with axially loaded polished specimens. Fatigue cracks were initiated from oxide defects in the squeezecast castings and from both oxide defects and shrinkage pores in the semisolid and gravity castings. Despite differences in the microstructures and in the defect populations in the squeeze and semisolid castings, their fatigue properties were similar. The fatigue properties of the gravity diecastings were inferior to the other two types. Previous reports that the fatigue properties of semisolid castings are inherently superior to those of other types of castings may be in error. Measurements of the sizes and types of the defects that initiate fatigue are reported.

1 INTRODUCTION

It has long been known that the fatigue endurance of castings is sensitive to the size of casting defects [1] and there is some evidence that it is also affected, but to a lesser extent, by solidification time (in the case of aluminium castings solidification time is reflected in dendrite arm spacing and the size of silicon particles [2, 3] and also porosity). The porosity of semisolid and squeeze castings is very low and so the processes should be capable of providing fatigue-resistant castings. However, there are surprisingly few references to the fatigue properties of such castings although semisolid casting has been promoted as a "high integrity" casting process for at least 20 years and squeeze casting for far longer. For squeeze casting of Al-7Si-xMg alloys, some authors [4] report an improved fatigue resistance and for semisolid castings, especially, there are claims [5] of a greatly enhanced performance. In this paper we report observations on the fatigue properties of squeeze and semisolid Al-7Si-0.3Mg castings made in the CSIRO foundry and on gravity diecastings made by Teksid. The fatigue strengths are rationalised in terms of the observed microstructures and to the defect types and sizes.

2 EXPERIMENTAL METHODS

2.1 Materials

Squeeze casting was done with AC601 ingot supplied by Comalco Aluminium and alloyed to match the thixotropic billet used for semisolid casting. Semisolid casting was done with electromagnetically stirred direct-chill cast thixotropic billets, supplied by Aluminium Pechiney. Gravity diecastings were done with commercial Sr-modified ingot of two compositions, here denoted as "low" and "high" Mg. Chemical analyses as determined by inductively coupled plasma - optical emission spectrometry (ICP-OES) are given in Table 1.

Table 1 Chemical composition, wt%, of the alloys

	Si	Mg	Sr	Fe	Ti
squeezecastings	6.8	0.36	0.03	0.08	0.01
semisolid castings	6.8	0.33	0.01	0.10	
gravity diecastings (low Mg)	7.0-7.4	0.28-0.33	0.03	0.12 – 0.19	0.14-0.18
gravity diecastings (high Mg)	7.1-7.4	0.74-0.90	0.03	0.14-0.16	0.14-0.20

2.2 Design of castings, casting procedure and heat-treatment. A stepped plate casting (Figure 1) was used for the squeeze and semisolid castings made at CSIRO. Squeeze casting followed the procedure of Chen and Thorpe [6] and semisolid casting was done as described by Chen and Davidson [7]. Gravity diecasting at Teksid was done in a steel mould to provide stepped plate castings of the same shape as those at CSIRO. The 10 mm and 15 mm steps were cut from the plates and were solution treated for 6 h at 540°C, quenched into water at 25°C, naturally aged for 20 h and, finally, artificially aged for 6 h at 170°C. This produced a very slightly under-aged condition (peak hardness typically occurs at 8 h).

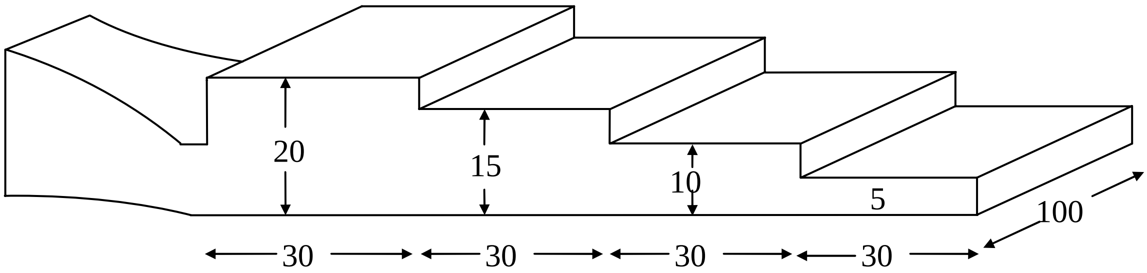


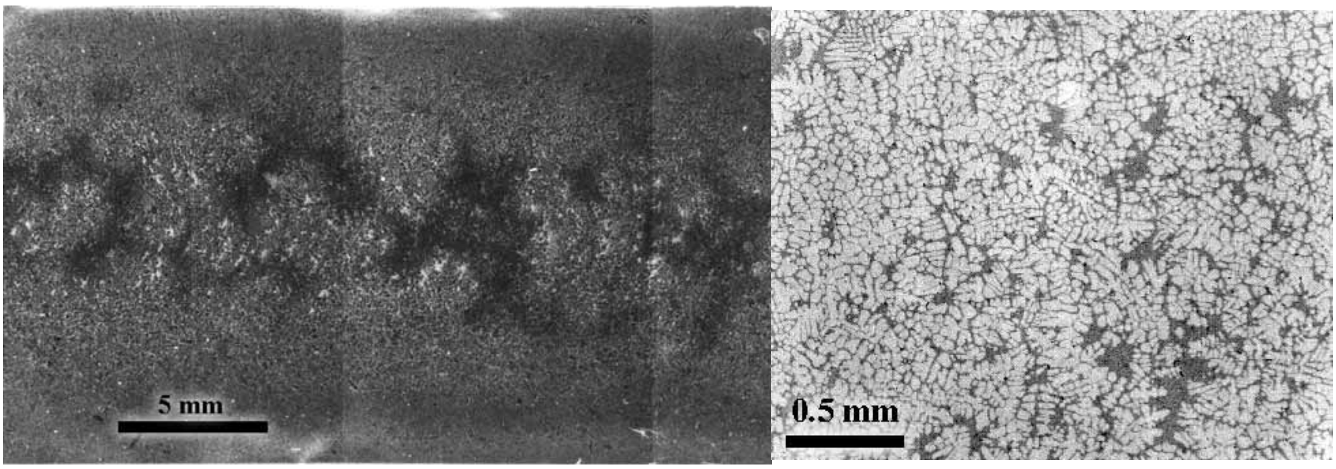
Figure 1: The cast plate (ingate on left-hand side, dimensions mm).

2.3 Fatigue testing. The heat-treated bars were machined into cylindrical test specimens with a gauge length of 10 mm, a gauge diameter of 5 mm and oriented with the tensile axis parallel to the width of the cast plate. Fatigue tests were done in a servo-hydraulic machine in sinusoidal force control at zero mean stress. The ambient temperature varied between 22 and 26°C and the relative humidity was usually between 30% and 40%.

3 RESULTS

3.1 Microstructures of the cast plates

Squeeze cast plates. Figure 2(a) shows the macrosegregation typical of squeeze castings and Figure 2(b) shows the dendritic structure. The darker mottled pattern along the centreline of the casting is associated with a fine eutectic structure, incorporating some very fine dendrites, indicating a short solidification time. These regions are the last to solidify and they reveal the local feeding channels.



(a) (b)

Figure 2: The squeezecast plate (15 mm step): (a) macrostructure, and (b) the dendritic structure

Semisolid cast plates. The microstructure consisted of coarse primary Al-phase globules (nondendritic) surrounded by eutectic and other minor phases, as is typical of semisolid castings.

No differences could be observed between the 10 and 15 mm thick sections of the plates. The structure is shown in Figure 3.

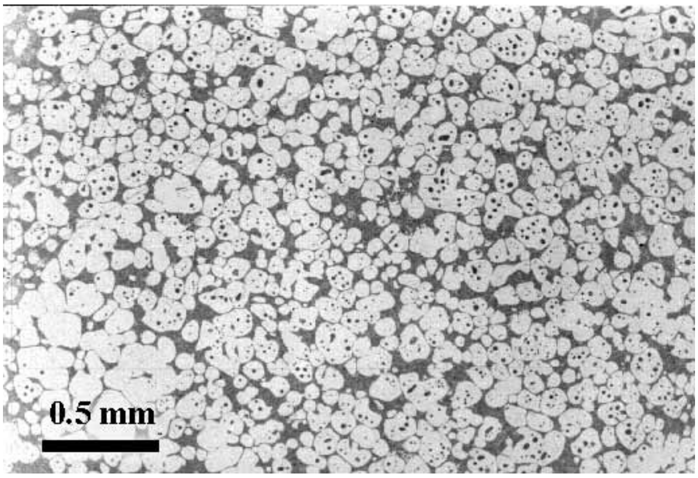


Figure 3: Microstructure of the semisolid casting.

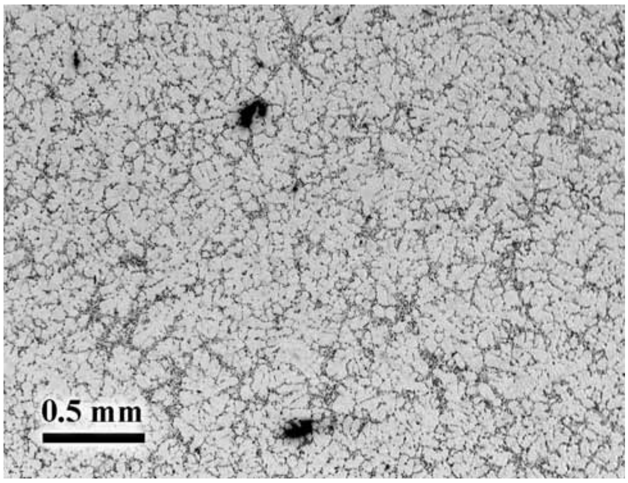


Figure 4: Microstructure of the gravity diecasting

Gravity diecast plates. These had a typical dendritic microstructure with a modified eutectic. An example if the microstructure is shown in Figure 4. The microstructure had more porosity than the squeeze cast one, but smaller pockets of eutectic.

3.2 Tensile and hardness properties.

The tensile and hardness properties are shown in Table 2 and are typical for A356-T6 castings.

Table 2: Tensile and hardness properties

	0.2% proof stress MPa	tensile strength MPa	elongation %	hardness (VPN, 10kgf)
squeeze	267	335	12	113
semisolid	267	321	15	114
gravity (low Mg)	234	298	8	101
gravity (high Mg)	323	359	2	128

3.3 Fatigue tests. Figure 5 shows the S-N curves for the squeeze and semisolid cast plates. There is only a slight difference between the two types of casting. The tests were terminated at 10^7 cycles, the fatigue strength at this life being determined by the staircase procedure [8] using a stress increment of 10 MPa and 15 samples. These 10^7 cycle strengths were 130 MPa for squeeze castings, 135 MPa for semisolid castings and 110 MPa for both the high Mg and low Mg gravity diecastings (data for gravity diecastings are not shown in Figure 5 for clarity). The standard deviations for the measurements are about 10 MPa so the data for the squeeze and semisolid castings are essentially indistinguishable. The line drawn on the Figure is taken from the Design Guidelines for Squeeze Castings [4] and it can be seen that it describes the present data well.

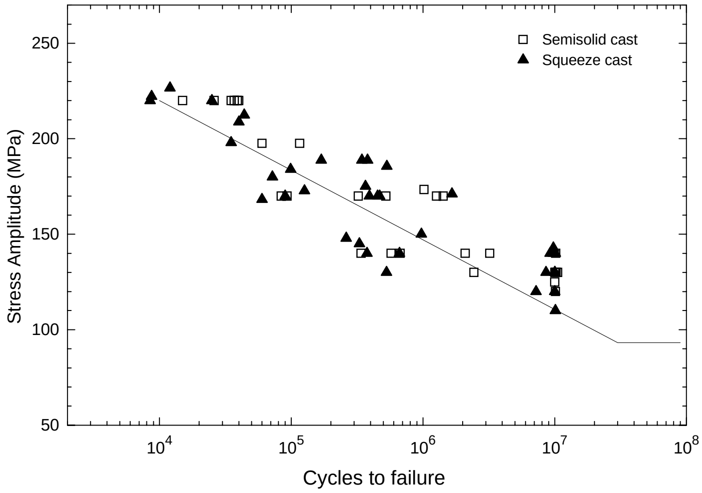


Figure 5: Fatigue data for squeeze and semisolid cast plates (R = -1)

3.3 Fractography

Squeeze castings. In all but 2 of the 42 specimens examined, fatigue cracks initiated from oxide defects. The sizes (areas) of the defects were measured and the median value was 0.042 mm^2.

Semisolid castings. In all but 6 of the 30 specimens examined it was possible to identify a casting defect at the crack origin. Of the 24 identified defects, 12 were oxide films and 12 were shrinkage pores. The area of each defect was measured and the observations are summarised in Table 3.

Table 3. Defects that initiated fatigue failures in semisolid castings

	type of defect		
	pores	oxides	unresolved
number	12	12	6
median area (mm^2)	0.02	0.02	

Gravity diecastings. As with the semisolid castings, fatigue cracks were initiated from both oxide defects and shrinkage pores and the data are shown in Table 5.

Table 4: Defects that initiated fatigue failures in gravity diecastings

low Mg alloy			
	pores	oxides	unresolved
number	5	14	3
median area (mm^2)	0.03	0.10	
high Mg alloy			
	pores	oxides	unresolved
number	9	8	1
median area (mm^2)	0.07	0.13	

4 DISCUSSION

Questions are often asked about mechanical properties that are characteristic of particular casting techniques, and design curves are produced purporting to show the fatigue properties of alloys cast by a particular method. An example is the design curve for squeeze castings shown in Figure 5 [4]. However, as has been known for over 50 years [1], a database for the fatigue properties of a particular alloy should contain size estimates for the defect population as well as the usual details of composition and heat-treatment condition. To illustrate this we summarise the present data in Table 5.

Table 5. Fatigue strengths of Al-Si-Mg-T6 castings at 107 cycles at R = -1 for three casting methods

casting method	alloy composition wt% Mg	Fe	proof stress MPa	fatigue strength MPa	dominant defect type	median defect area mm^2
semisolid	0.35	0.11	267	135	oxide/porosity	0.02
squeeze	0.36	0.13	267	130	oxide	0.04
gravity	0.30	0.16	234	111	oxide/porosity	0.08
gravity	0.70	0.14	323	110	oxide/porosity	0.08

The data in Table 5 conform qualitatively to the concept that the fatigue strength increases as the defect size decreases. They also show the marked improvement in the two "high integrity" castings compared with gravity diecasting. However the quantitative agreement with the scaling rule described below between fatigue strength and defect area is only moderate.

The relationship between the fatigue life, N_f, the stress amplitude, σ_a, and a length dimension, a_i, which characterises the size of the defect can be found by integrating the Paris Equation for fatigue crack growth [9, 10, 11, 12]. An approximate solution is

$$\sigma_a^m N_f a_i^{(m-2)/2} = \mathrm{B} \tag{1}$$

in which m is the Paris exponent and the constant, B, includes the Paris Law pre-exponential term and various other terms including the assumed relation between the stress amplitude and the effective stress. We assume that m = 4 [9] and, since A_i, the defect area, is proportional to a_i^2, it follows that

$$\sigma_a^4 N_f A_i^{1/2} = \mathrm{B}' \tag{2}$$

in which B' includes the constant of proportionality between a_i and A_i. Equation (2) shows that the fatigue strength at a given life should be proportional to $A_i^{-1/8}$. From Table 5 the fatigue strengths of semisolid, squeeze and gravity castings should be in the ratios of 1.19:1.09:1.00 whereas in fact they are in the ratios of 1.22:1.17:1.00.

There are several reasons why the observed fatigue strengths may not conform exactly to Equation 2. The principal one is that we have not, as yet, carried out crack propagation experiments to measure the constants in the Paris equation and have assumed here that they are the same for all castings. Similarly, we have no information on how crack closure and threshold effects vary with microstructure. As regards threshold effects, no initiating defect was found in 6 of the 30 semisolid specimens. The smallest defect observed had an area of 0.002 mm^2 and one possibility for the "defect-free" specimens is that the defects simply could not be seen. An alternative possibility is that the figure of ~0.002 mm^2 is a lower limit beyond which, as suggested by others [13,14,9], other fatigue crack initiation mechanisms come into operation. If this second alternative is true then the observed fatigue limit of ~135 MPa is close to the limit for this alloy, regardless of further decreases in casting defect size.

We have not separated the effects of oxide defects and shrinkage pores on fatigue life. It may be significant that the fatigue strengths of the semisolid and squeeze castings are similar despite the differences in defect size (0.02 mm^2 and 0.04 mm^2, respectively). This is indirect support for the idea, suggested by Wang [15], that oxide defects are less significant than pores of the same size.

The high incidence of oxide defects as the initiating defects in the gravity diecastings is not typical of castings made under laboratory conditions and it suggests either that filtering of the melt was not optimum or that excessive turbulence had occurred during the pour: this comment is supported by the low ductilities of these castings as reported in Table 2.

5 CONCLUSIONS

The following conclusions can be made regarding this work:

(i) The fatigue strengths of semisolid castings made for this project were similar to those of squeeze castings made in the same die.

(ii) The fatigue properties of the squeeze castings produced here are described well by the published design curve for squeeze castings despite the lack of information on defect populations underlying the design curve.

(iii) The fatigue strengths of semisolid and gravity diecastings are determined by both oxides or pores while that of squeeze castings is determined by oxides.

(iv) The initiating defects in semisolid castings were somewhat smaller than the oxide films in squeeze castings made in the same machine.

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